

# ‘Notches’ in the Average Profiles of Bright Pulsars

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## ABSTRACT

We discuss the discovery of ‘notch-like’ features in the mean pulse profile of the nearby, bright pulsar B0950+08. We compare these low-level features with those previously seen in the pulse profiles of pulsars J0437–4715 and B1929+10. While J0437–4715 is a binary millisecond pulsar and B0950+08 and B1929+10 are isolated, slow pulsars, all three pulsars are nearby and very bright. Furthermore, all three have detectable emission over an unusually wide range of pulse phase. We describe the similar properties of the notch features seen in all three pulsars and discuss possible interpretations.

## 1 INTRODUCTION

Detailed studies of the structure of radio pulsar pulse profiles are essential for understanding the pulsar emission mechanism and the forms of the pulsar emission beam. Pulse profiles are remarkably stable over timescales ranging from a few pulses to many years, indicating that these profiles are determined by permanent physical characteristics of the neutron star and its environment. Many profile properties can be explained very well by the “hollow-cone” model of pulsar emission developed by Radhakrishnan & Cooke (1969) and Komesaroff (1970), shortly after the discovery of the first pulsar. This “magnetic-pole” model, further developed by Sturrock (1971) and Ruderman & Sutherland (1975), involves charges streaming from the polar cap along the open field lines, radiating in the direction of their motion and forming an emission cone aligned with the magnetic axis of the star. As more pulsars were discovered, many were found to have two, three or even more pulse components, prompting various efforts to classify and interpret the various forms (*e.g.* Backer 1973; Rankin 1983, 1993; Lyne & Manchester 1988).

In this paper we draw attention to the strange “notches” in the profiles of B0950+08 and two other pulsars, J0437–4715 and B1929+10. All three stars exhibit very similar double “notch” features which appear to have virtually nothing to do with the component structures of their very different profiles. B0950+08 and B1929+10 have rotational periods of 253 and 227 ms, whereas J0437–4715 is a binary millisecond pulsar with a period of only 5.75 ms. Significantly, these stars are some of the very closest among the pulsar population—all with dispersion measures (DMs) of about 3 pc cm<sup>−3</sup> and parallax-determined distances of some 262±5, 331±10 and 170±3 pc (Briskin *et al* 2000, 2002)—and, in spite of the fact that they all have rather ordinary spindown values, all have been detected in the optical and/or soft x-ray region (Mignani *et al* 2002; De Luca *et al* 2003; Wang *et al* 1997; Zavlin *et al* 2002). B0950+08 and B1929+10 are among the brightest pulsars

in the radio sky (Taylor *et al* 1993), and J0437–4715 is well known as the brightest millisecond pulsar. In §2 we discuss our observations of B0950+08, present its average pulse profiles and describe the unusual features. In §3 we compare these features with similar ones seen in the profiles of J0437–4715 and B1929+10 and discuss possible physical interpretations.

## 2 OBSERVATIONS AND RESULTS

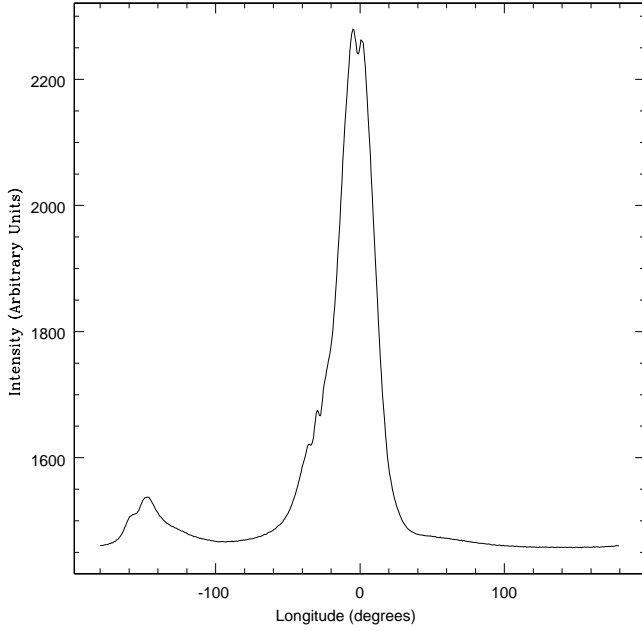
Observations presented in this section were made using the 305-m Arecibo Telescope in Puerto Rico. Observations at 430 MHz were obtained using the Arecibo Observatory Fourier Transform Machine (AOFTM<sup>★</sup>) with 1024 channels across a 10-MHz bandpass and with 409.6-μs sampling. B0950+08 was observed at 430 MHz on MJDs 51182, 51188 and 51189 (4th, 10th and 11th of January, 1999) for durations of 3000, 3700 and 2500 seconds, respectively. The 1475-MHz data presented were acquired with the Wideband Arecibo Pulsar Processor (WAPP<sup>†</sup>) with 128 channels across a 100-MHz bandpass and 256-μs sampling. Observations of B0950+08 at this frequency were taken on MJDs 52187 and 52189 (5th and 7th of October, 2001) for durations of 1100 and 7200 seconds, respectively.

For each B0950+08 observation, pulse phases were calculated using the software package TEMPO<sup>‡</sup> (Taylor & Weisberg 1989) and an ephemeris obtained at Jodrell Bank Observatory (Hobbs 2002). Data were folded to create mean pulse profiles. The up-to-date ephemeris allowed alignment of the profiles acquired on different dates and at different frequencies. The 430-MHz average profiles for the MJD 51188 and 51189 observations are presented in Figs. 1 and 3. Note that the two profiles are distinctly different in

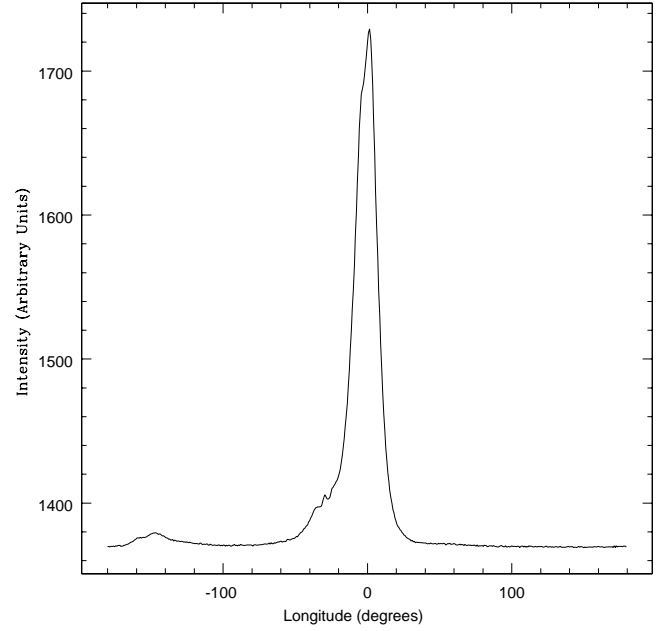
★ <http://www.naic.edu/aof tm>

† <http://www.naic.edu/wapp>

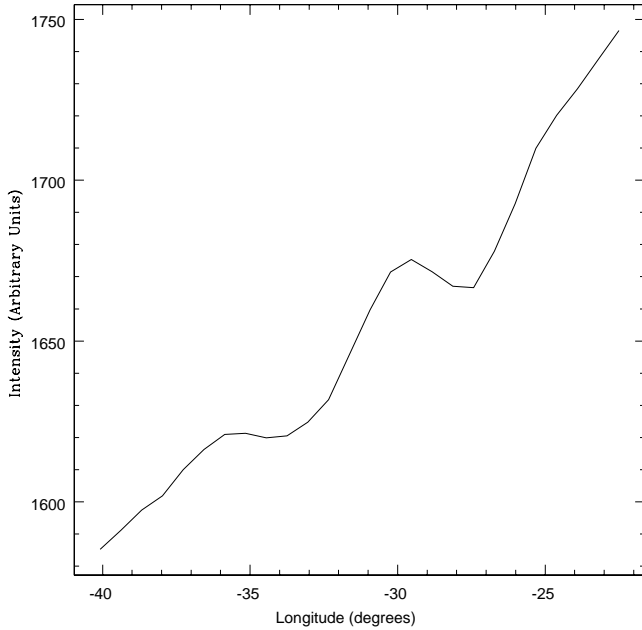
‡ <http://pulsar.princeton.edu/tempo>



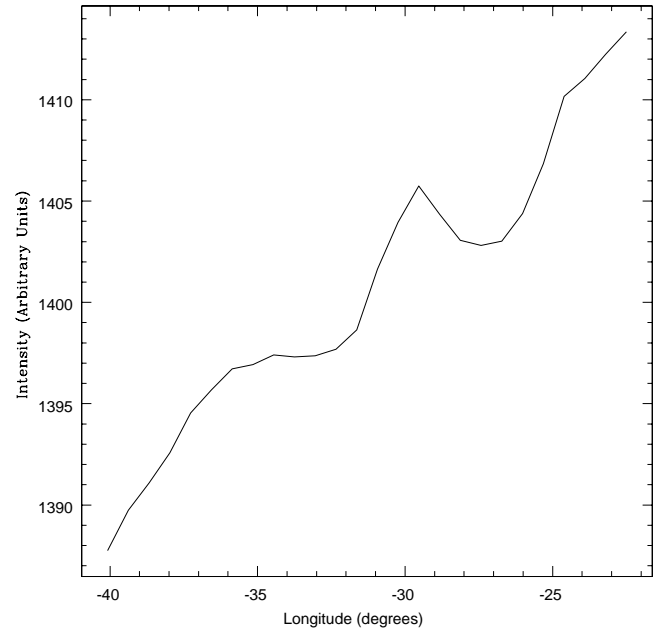
**Figure 1.** Pulse profile for B0950+08 taken on MJD 51188 at 430 MHz for a total observation length of 3700 s. A bandwidth of 10 MHz and sampling time of  $409.6 \mu\text{s}$  were used. Data were folded using 512 bins across the pulse period of 253 ms. The “notch” pair at a longitude of  $-30^\circ$  is apparent.



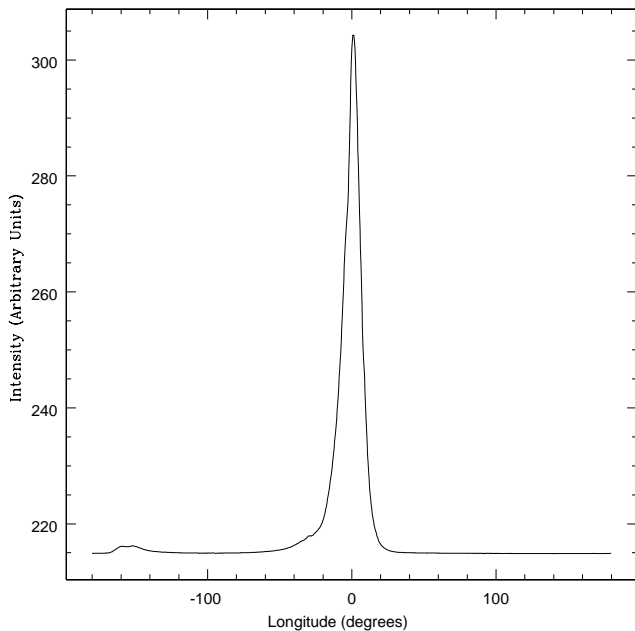
**Figure 3.** Pulse profile for B0950+08 taken on MJD 51189 at 430 MHz for a total observation length of 2500 s. Note that while this profile and that of Fig. 1 have very different forms, the “notch” pair at  $-30^\circ$  falls at precisely the same longitude (see text).



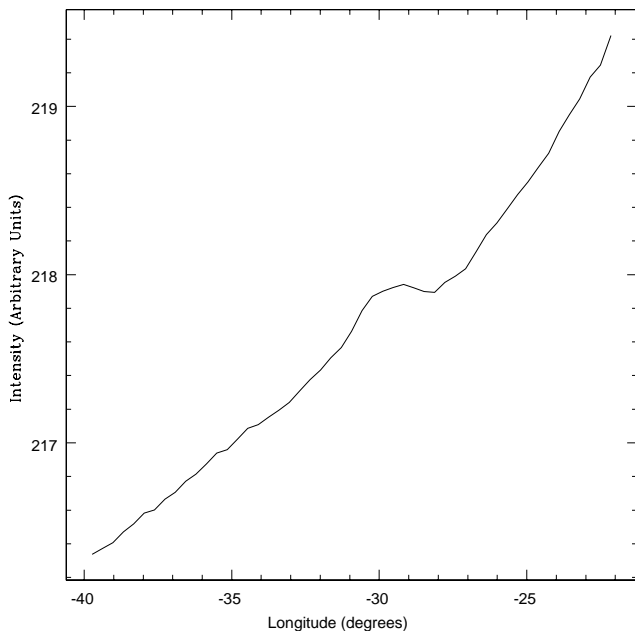
**Figure 2.** The profile of Fig. 1 with a smaller longitude scale. The notch feature at longitude  $-30^\circ$  is well defined. Identical features with the same morphology and phase were seen at this frequency in observations on MJDs 51182 and 51189.



**Figure 4.** The profile of Fig. 3 with a smaller longitude scale. Here again, the feature at  $-30^\circ$  is clear.



**Figure 5.** Pulse profile for B0950+08 on MJD 52189 at 1475 MHz for a total observation length of 7200 s. A bandwidth of 100 MHz and sampling time of  $256 \mu\text{s}$  were used. Data were folded using 1024 bins across the pulse period of 253 ms. The notch feature at longitude  $-30^\circ$  is barely apparent on this scale.



**Figure 6.** The profile of Fig. 5 with a smaller longitude scale. Here the feature at  $-30^\circ$  is clear. An identical feature with the same morphology and phase was seen on MJD 52187.

overall form, but that the low-level features are seen at just the same  $-30^\circ$  longitude before the main pulse (MP) peak (see Figs. 2 & 4). Moreover, a similar pair of features is seen in the MJD 51182 data (not shown).

In Fig. 5 we present a corresponding 1475-MHz profile for the MJD 52189 observation, where again a low-level feature is seen at some  $-30^\circ$  (see Fig. 6). At 430 MHz the feature consists of two dips in the profile intensity with half widths of some  $2^\circ$  and their centers separated by some  $7^\circ$ . The total width of the feature at 430 MHz is  $11^\circ$ . At 1475 MHz—in both this observation and another (not shown) on MJD 52187—the feature appears as a single peak with a width of  $3^\circ$ .

Several published observations also appear to record the B0950+08 “notches”. They are very clear in the 430-MHz time-aligned profile of Hankins & Rankin (2003), but cannot be discerned in the lower quality observations at various other frequencies. Moreover, the “notches” can probably be seen in the polarimetric observations of both Gould & Lyne (1998) and Weisberg *et al* (1998). The former very high quality profiles seem to show pairs of features at the correct phase at 408, 610 and 925 MHz, and in the latter we appear to see a *pair* of features at 1418 MHz. This latter observation (see their Fig. 5) is especially interesting because the features appear to involve the linear polarization also, which is only 20–30% in the region on the far leading edge of the profile.

It must be said that the features in B0950+08 are rather weak, at best reducing the intensity at their centers by a few percent. It might even be regarded as surprising that such features would be found in a star which is well known for its sporadic emission (It may not be known, for instance, whether the pulsar ever nulls, because the range of intensities exhibited by its pulses is so large.) In this context, it is interesting that Nowakowski *et al* (2003) have shown that this pulsar’s profile is comprised of different intensity fractions which have quite different partial-average profile forms. These studies indicate that the MP has three main “components”: the trailing one which is usually strongest, the middle one which varies in relative intensity, and a leading one which can only be discerned in certain populations of weak pulses. It would therefore appear that the distinct 430-MHz profiles seen above represent distinct profile “modes” in this star. Finally, the above study finds that the “notches” are seen only in the very weakest populations of pulses, which nonetheless contribute significant power to the profile. The authors believe that the weakest pulses represent emission from rather higher altitudes than the stronger fractions.

### 3 DISCUSSION

Unusual features similar to those presented in §2 have been observed in two other pulsars. Rankin & Rathnasree (1997) reported a double notch-like feature in the average profile of B1929+10 at 430 MHz, and a display similar to theirs using the same observations is given in Fig. 7. As can be seen there, the “notches” follow the main pulse peak by roughly  $100^\circ$  and have a total width of approximately  $10^\circ$ . More accurate scaling reveals that they have widths of some  $2.3^\circ$  and that their centers are separated by just twice this

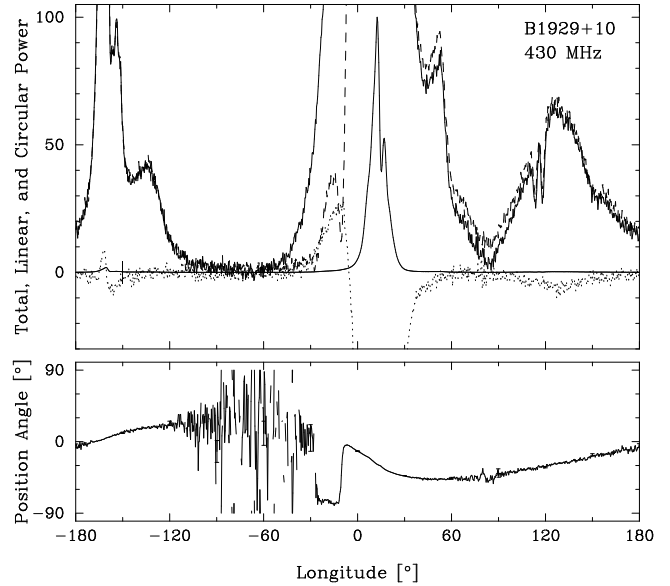
interval. Note also that B1929+10’s profile is generally fully linearly polarized, so that the features are most clearly seen in both the total power and total linear polarization<sup>§</sup>, where they represent about a 40% diminution of the power at their centers. The “notches” do appear to be just visible in a sensitive 430-MHz observation of Blaskiewicz *et al* (1991: see their Fig. 22), though they are not seen at 1.4 GHz either in this paper or in Rankin & Rathnasree. This may be due to the overall weakening of the broad low-level emission feature that follows the MP as well as the poorer signal-to-noise of the 21-cm observations. Neither, unfortunately, were the recent observations of Weisberg *et al* (2003) sufficiently sensitive to detect the features.

Similar features have also been observed by Navarro *et al* (1997) in the average profile of the millisecond pulsar J0437–4715. These “notches” fall on the trailing edge of this star’s very broad profile, some 70° after the bright central component. Here, the pair is separated by about 3.3°, the half-power widths are about a degree, and the fractional intensity decrease at their centers is about 50%. These characteristics are clearly seen in the 1512-MHz polarization profile of Navarro *et al* (their Fig. 4) which we reproduce here as Fig. 8. However, this paper reports additional detections at frequencies of 438 and 660 MHz, and the three total-power profiles appear together in our Fig. 9, aligned (according to their Fig. 5 caption) on the basis of the anti-symmetric circularly polarized signature associated with the central component. One can see that the “notches” at the three frequencies do not quite align, falling slightly earlier at 660 and 1512 MHz. However, were the profiles aligned more nearly according to the centroids of the central component, the “notches” might well fall at just the same profile phase. It would be interesting to see the results of a timing alignment as carried out for B0950+08 above. Finally, the features do appear to evolve somewhat with frequency, becoming wider and more separated at lower frequencies.

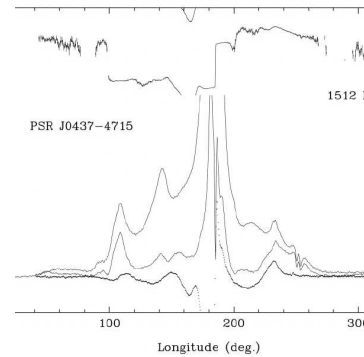
It is noteworthy that, for all three pulsars, these unprecedented features have roughly the same angular width, implying that their overall scale is some nearly fixed fraction of the rotational cycle of the star [as, apparently, is also the case for pulsar microstructure (*e.g.*, Popov *et al* 2002)]. Furthermore, for the two pulsars in which the features have been detected at more than one frequency, they seem to appear at exactly the same longitude. Again, this is a well-known feature of pulsar microstructure, implying that the two phenomena derive from the same physical regions in the pulsar magnetosphere. Pulsar microstructure generally shows the same width regardless of frequency, however, there is evidence for the width of the notch features decreasing with frequency.

B0950+08 and B1929+10 have remarkably similar properties. Both are very bright, have quarter-second rotational periods, and are very nearby. Both pulsars have

<sup>§</sup> The possible origin of this strange “superpolarization”, that was also seen by Phillips (1990), is discussed in Rankin & Rathnasree (1997). Phillips, however, seems to have plotted his Figs. 1 & 2 with some unreported smoothing, so that the “notches” are not visible, though there is a broad dip in the power just where they should be.



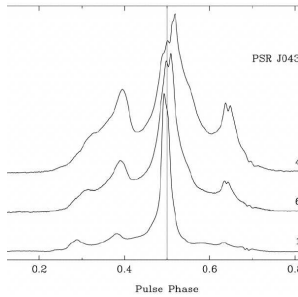
**Figure 7.** Full-period average polarization profile of B1929+10 at 430 MHz after Rankin & Rathnasree (1997). The total power (Stokes  $I$ ) is plotted first at full scale and then at a  $\times 250$  expanded scale, so that only features below 0.4 percent of the MP amplitude are now visible. The linear ( $L$ ) and circular ( $V$ ) polarization are then plotted at the expanded scale. The PA is plotted in the lower panel. Note the double “notch” feature which follows the MP by about 100°. This region exhibits complete linear polarization (see text), so the “notches” are clearly visible in both  $I$  and  $L$ , representing an intensity decrease at their centers of some 40%.



**Figure 8.** Polarized pulse profile for J0437–4715 at 1512 MHz from Navarro *et al* (1997); their Fig. 4.

detectable emission over an unusually broad fraction of their rotation cycle and both exhibit interpulses. With a spin period of 5.75 ms, J0437–4715 has very different spin-down properties; however, it is also nearby, extremely bright, and, while it has no interpulse, it has detectable emission over more than 180° of longitude.

The identification of these features in the three brightest pulsars with broad pulse profiles suggests that such features may be common among pulsars with broad profiles. As



**Figure 9.** Total-intensity profiles for J0437–4715 at 438, 660 and 1512 MHz, which have been aligned according to the zero-crossing point of the anti-symmetric circular polarization under their central components from Navarro *et al* (1997); their Fig. 5. Note that the “notches” almost align—and that they could even do so more closely if only a slightly different alignment had been used.

they are apparently seen over a substantial portion of the radio band and evolve little with frequency, it would seem that they cannot be attributed to absorption in any usual sense. Thus it would seem that they are either due to some very puzzling aspect of the emission process or represent an equally puzzling obscuration of the emission along our sight line. While we cannot more than speculate about the causes of these features, a very novel mechanism is being suggested by Wright (2003) in a companion paper. Clearly, few pulsars show emission so far from the main pulse or interpulse, so observing this feature in more pulsars will be very difficult until the advent of more sensitive pulsar instruments such as the SKA. However, future more sensitive multi-frequency observations of the pulsars discussed above, in addition to polarimetric observations, may yield more clues as to the origin of these unusual features.

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